Overview of Feasibility Studies on CE-5: Free Maneuvering
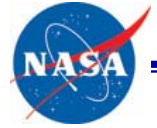
Dr. Karl Bilimoria

NASA Ames Research Center

<kbilimoria@mail.arc.nasa.gov>

DAG-TM Workshop

15 November 2002

Outline of Presentation

- Background

- Summary of selected studies
  - Properties of air traffic conflicts for free and structured routing
  - Performance evaluation of airborne separation assurance for Free Flight
  - System performance characteristics of centralized and decentralized air traffic separation strategies
  - Stability of intersecting aircraft streams with self-separation
  - Aircraft conflict resolution with an arrival time constraint
  - Agent-based approach to constrained conflict resolution

- Lessons learned

- Open research issues

Background

- Initial feasibility evaluation of Free Maneuvering operations
  - Focus on high-level performance characteristics and issues
  - Perfect information
  - No human in the loop

- Key issue: Effects of decentralized separation assurance
  - Can separation be maintained under decentralized rules?
  - What are the effects on system efficiency?
  - What are the implications for system stability (domino effect)?
  - What is the impact on conformance to local-TFM constraints?

- Numerous studies conducted (FY00 – FY02)
  - In-house work at Ames
  - RTO-36 and RTO-67 (Seagull)
  - Cooperative Agreements with MIT

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1. Bilimoria, K.D. and Lee, H.Q., "Aircraft Conflict Resolution with an Arrival Time Constraint," Paper No. 2002-4444, *AIAA Guidance, Navigation, and Control Conference,* August 2002.

2. Mueller, K.T., Schleicher, D., and Bilimoria, K.D., "Conflict Detection and Resolution with Traffic Flow Constraints," Paper No. 2002-4445, *AIAA Guidance, Navigation, and Control Conference*, August 2002.

3. Dugail, D., Feron, E., and Bilimoria, K.D., "Conflict-Free Conformance to En Route Flow-Rate Constraints," Paper No. 2002-5013, *AIAA Guidance, Navigation, and Control Conference*, August 2002.

4. Harper, K.A., Guarino, S.L., Hanson, M.L., Bilimoria, K.D., and Mulfinger, D.G., "An Agent-Based Approach to Aircraft Conflict Resolution with Spatial Constraints," Paper No. 2002-4552, *AIAA Guidance, Navigation, and Control Conference*, August 2002.

5. Dugail, D., Feron, E., and Bilimoria, K., "Stability of Intersecting Aircraft Flows using Heading Change Maneuvers for Conflict Avoidance," Paper INV-5005, *American Control Conference*, May 2002.

6. Krozel, J., Peters, M., Bilimoria, K.D., Lee, C., and Mitchell, J.S.B., "System Performance Characteristics of Centralized and Decentralized Air Traffic Separation Strategies," *4th USA/Europe Air Traffic Management Research and Development Seminar*, December 2001; also, *Air Traffic Control Quarterly*, Vol. 9, No. 4, December 2001, pp. 311–332.

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7. Bilimoria, K.D. and Lee, H.Q., "Properties of Air Traffic Conflicts for Free and Structured Routing," Paper No. 2001-4051, *AIAA Guidance, Navigation, and Control Conference*, August 2001.

8. Mao, Z.-H., Feron, E., and Bilimoria, K., "Stability and Performance of Intersecting Aircraft Flows under Decentralized Conflict Avoidance Rules," Paper No. 2000-4271, *AIAA Guidance, Navigation, and Control Conference*, August 2000; also, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 2, No. 2, June 2001, pp. 101–109.

9. Bilimoria, K.D., "A Geometric Optimization Approach to Aircraft Conflict Resolution," Paper No. 2000-4265, AIAA Guidance, Navigation, and Control Conference, August 2000.

10. Bilimoria, K.D., Sheth, K.S., Lee, H.Q., and Grabbe, S.R., "Performance Evaluation of Airborne Separation Assurance for Free Flight," Paper No. 2000-4269, *AIAA Guidance, Navigation, and Control Conference*, August 2000; also, *Air Traffic Control Quarterly*, to appear.

11. Bilimoria, K.D., Lee, H.Q., Mao, Z.-H., and Feron, E., "Comparison of Centralized and Decentralized Conflict Resolution Strategies for Multiple-Aircraft Problems," Paper No. 2000-4268, AIAA Guidance, Navigation, and Control Conference, August 2000.

Papers available upon request

Properties of Air Traffic Conflicts
for Free and Structured Routing

» Karl Bilimoria and Hilda Lee
Paper No. 2001-4051
AIAA Guidance, Navigation, and Control Conference
Montréal, CANADA
August 2001

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Problem Definition

- Research Questions:
  - How often would conflicts occur in the absence of corrective action?
  - What are the key properties of conflicts?
  - What is the level of interaction between individual conflicts?
  - Does free routing significantly change the number/nature of conflicts?

- Approach
  - Conduct simulation based on real traffic data from current operations
    - » Aircraft-to-aircraft conflicts only
    - » Wind effects not modeled
  - Study conflicts only in Class A airspace (at or above FL180)
    - » Trajectories in lower airspace can vary significantly from flight plans
    - » Significant percentage of flights in lower airspace are VFR flights

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Conflict Data Collection

- Enhanced Traffic Management System (ETMS) data for a 24-hr period in March 2001
  - 57,402 aircraft total
  - 37,926 aircraft in Class A airspace

- Birth points and times captured from ETMS data

- Aircraft fly to destination in 3-D simulation, with Conflict Resolution **OFF**
 - Free (great circle) routing
  - Structured (flight plan) routing

Aircraft Count vs. Time
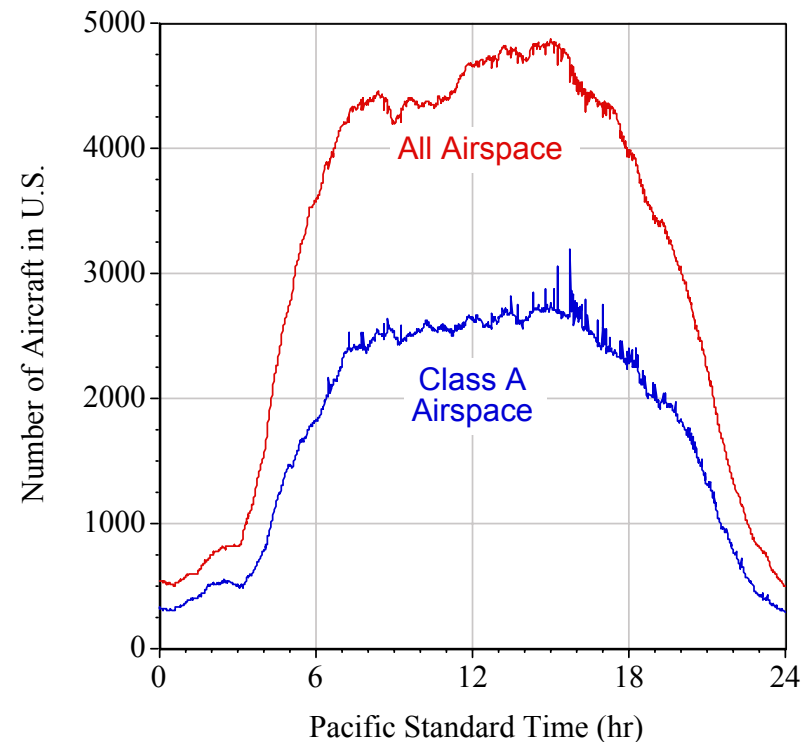
FACET: Future ATM Concepts Evaluation Tool

- Simulation tool for exploring advanced ATM concepts
  - Developed at NASA-Ames

- Airspace Modeling (over contiguous U.S.)
  - Center/sector boundaries
  - Jet/Victor airways
  - Navigation aids
  - Airports

- Trajectory Modeling
  - Fly flight-plan routes or direct (great circle) routes over round earth
  - Climb/descent performance models
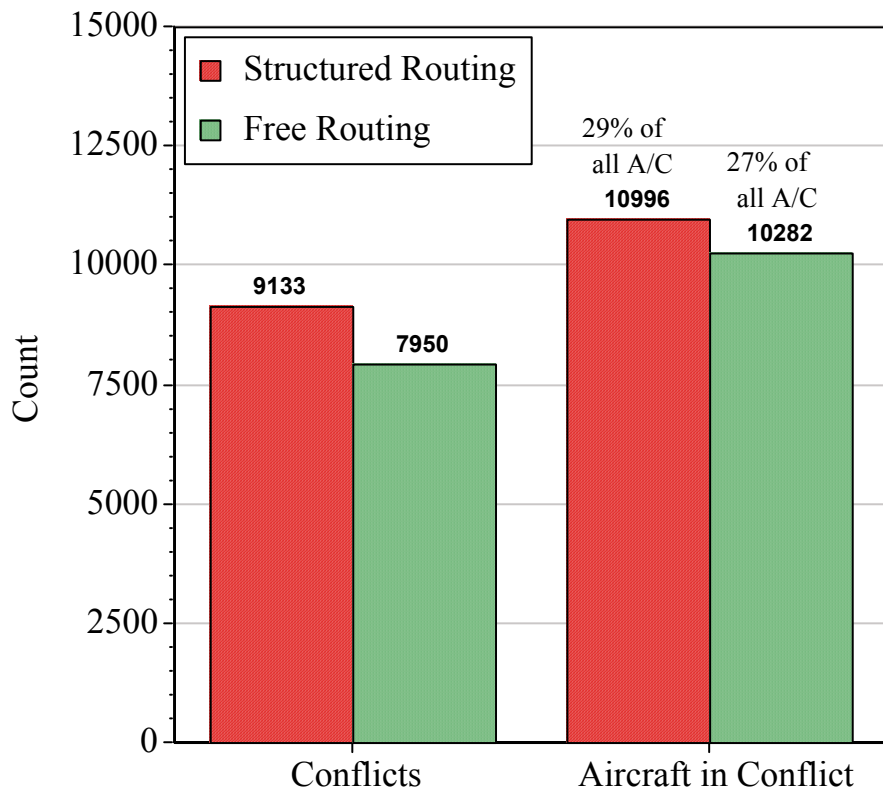 - Dynamic models for turns and acceleration/deceleration
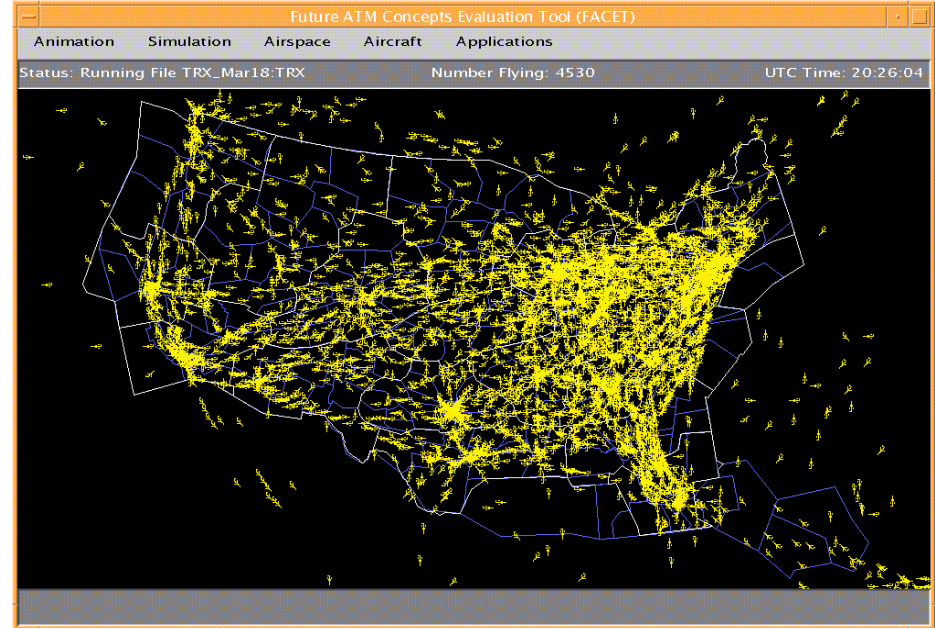
Bilimoria, K.D., Sridhar, B., Chatterji, G.B., Sheth, K.S., and Grabbe, S.R., "FACET: Future ATM Concepts Evaluation Tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1–20.
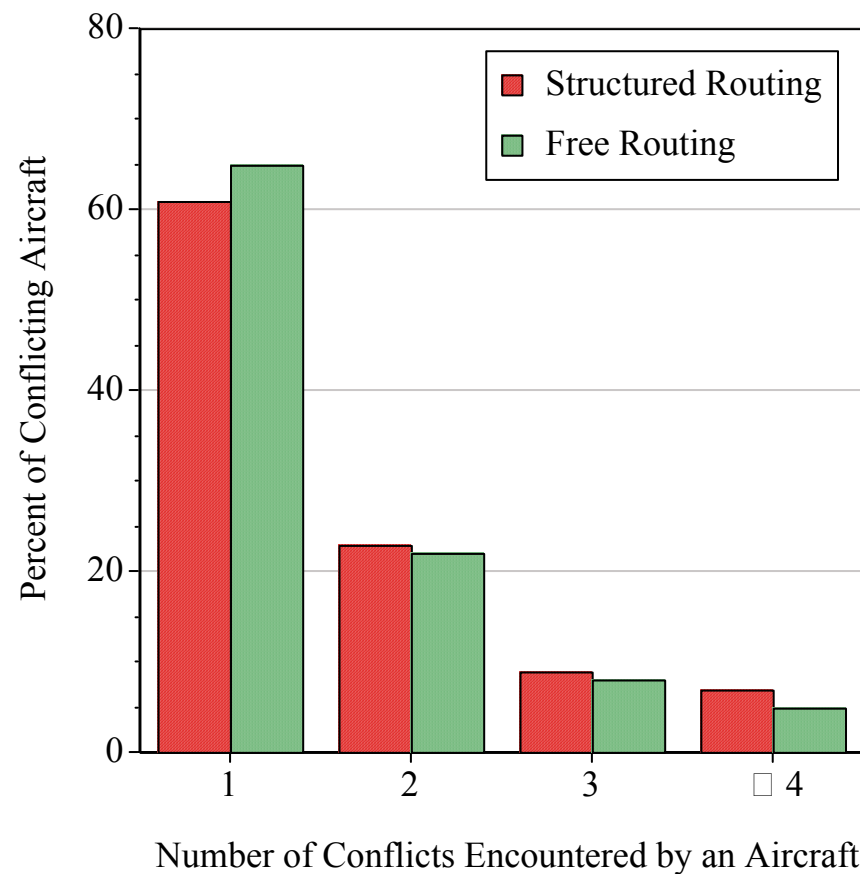
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Results: Number of Conflicts

Counts of Conflicts and Aircraft

Number of Conflicts per Aircraft

Number of Conflicts Encountered by an Aircraft

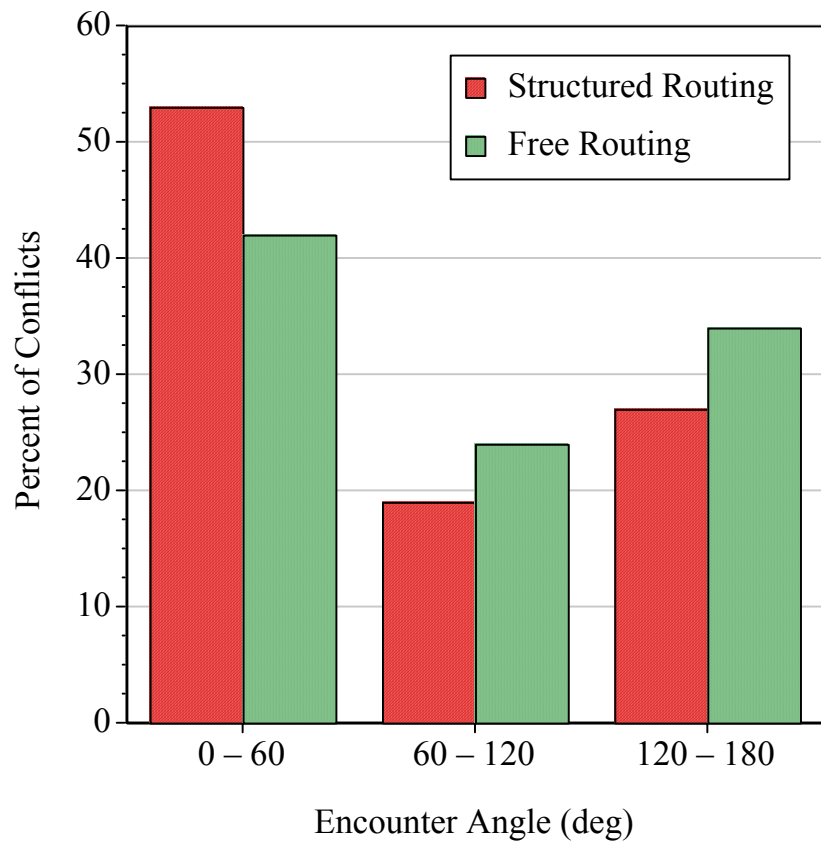Overview of Feasibility Studies on CE 5: Free Maneuvering

Structured Routing
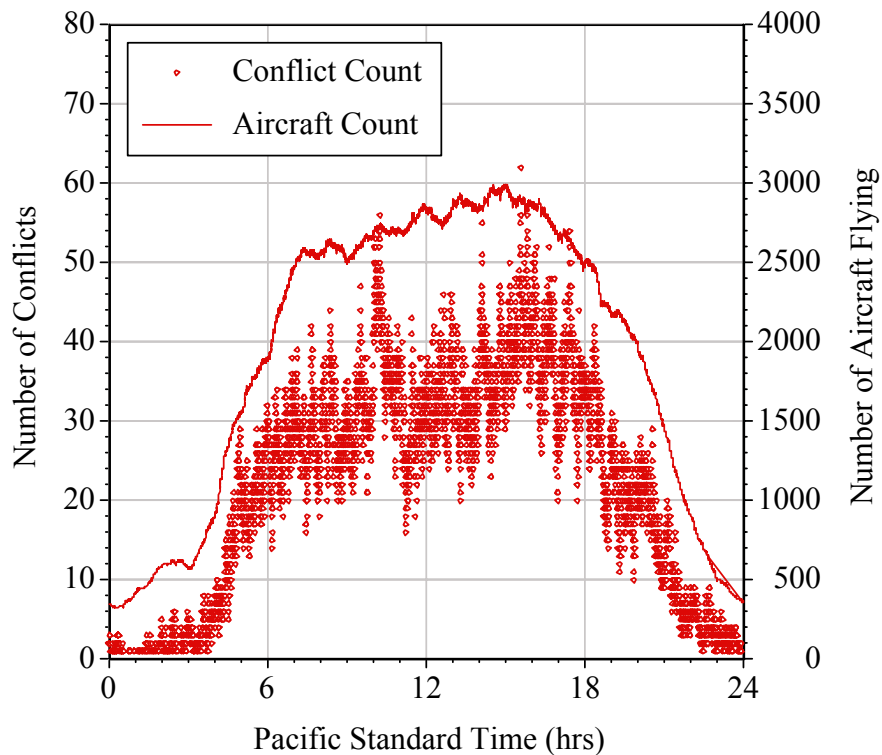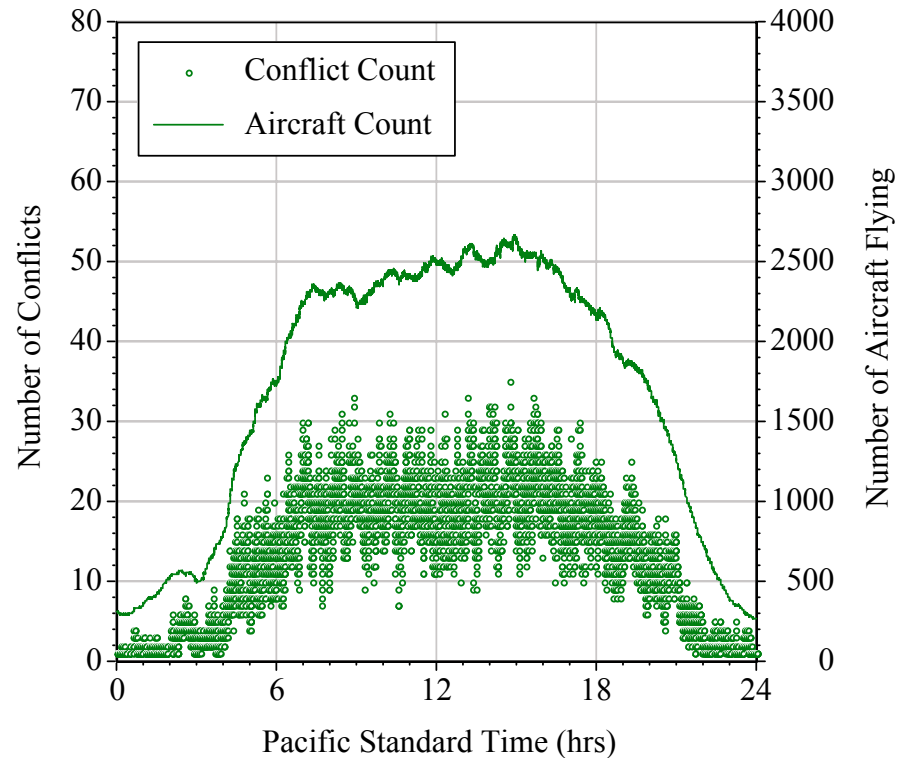
Free Routing

Results: Conflict Properties

Encounter Angle Distributions

Legend:
- Structured Routing (red)
- Free Routing (green)

X-axis: Encounter Angle (deg)
Y-axis: Percent of Conflicts

Altitude-Rate Distributions

Legend:
- Structured Routing (red)
- Free Routing (green)

X-axis: Altitude-Rate Combination
(L = Level; NL = Non-Level)
Y-axis: Percent of Conflicts
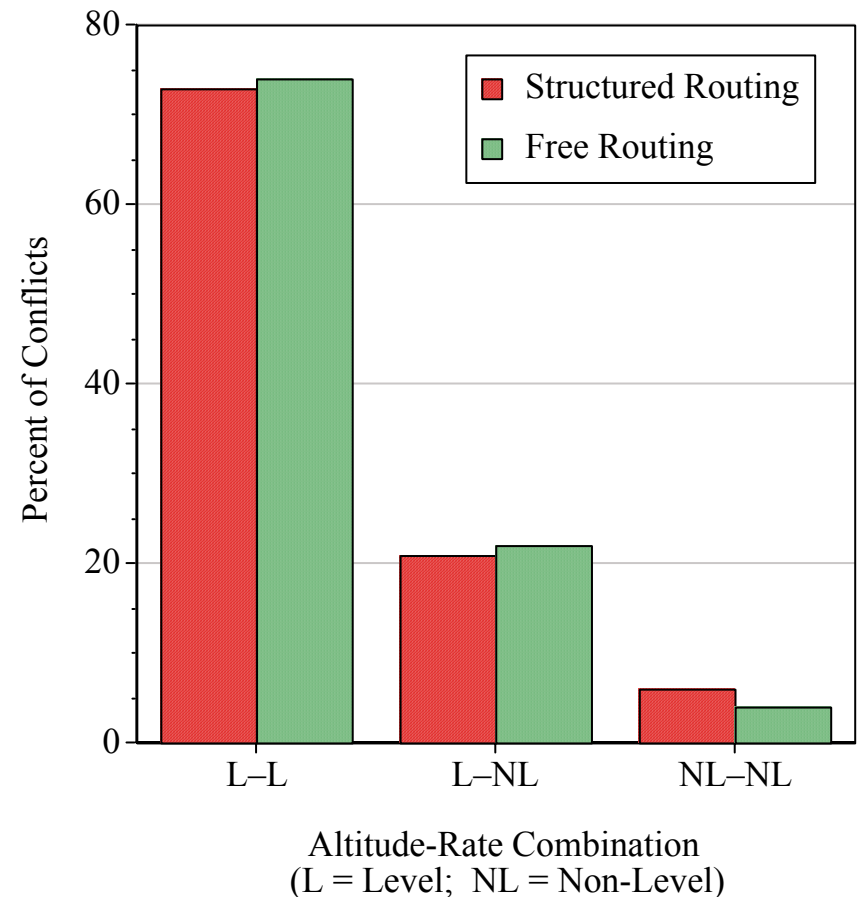
Results: Conflict Interactions

No Interaction

Weak Interaction

Strong Interaction

Structured Routing
Free Routing

Percent of Conflicts

84 | 92
10 | 6
6 | 2

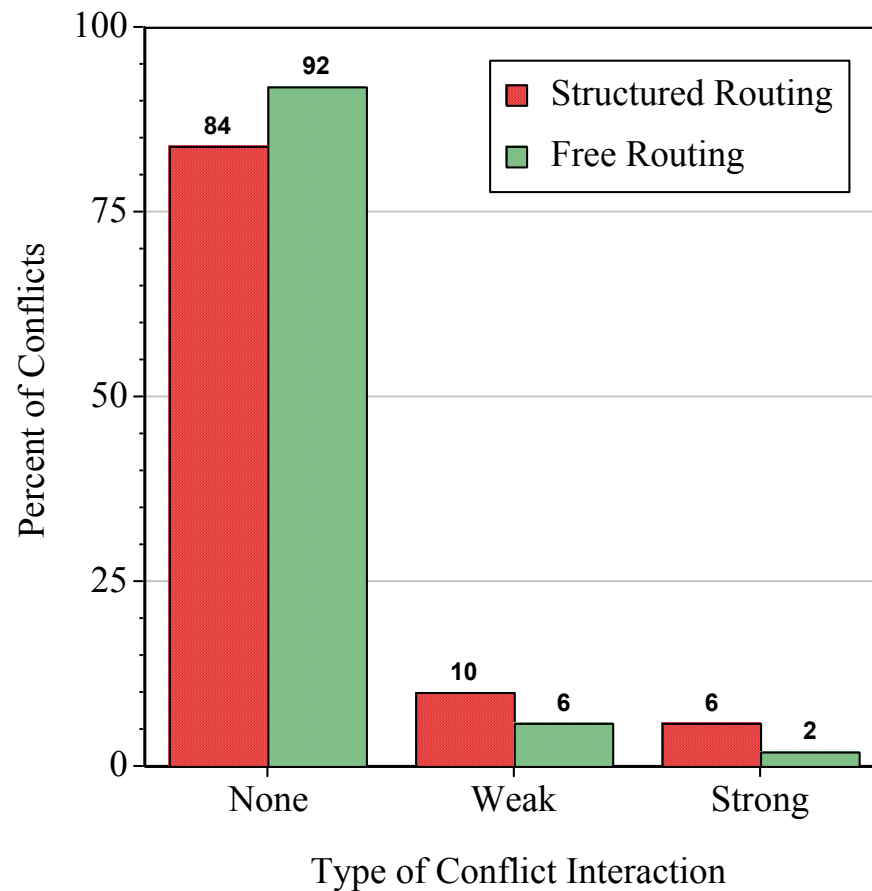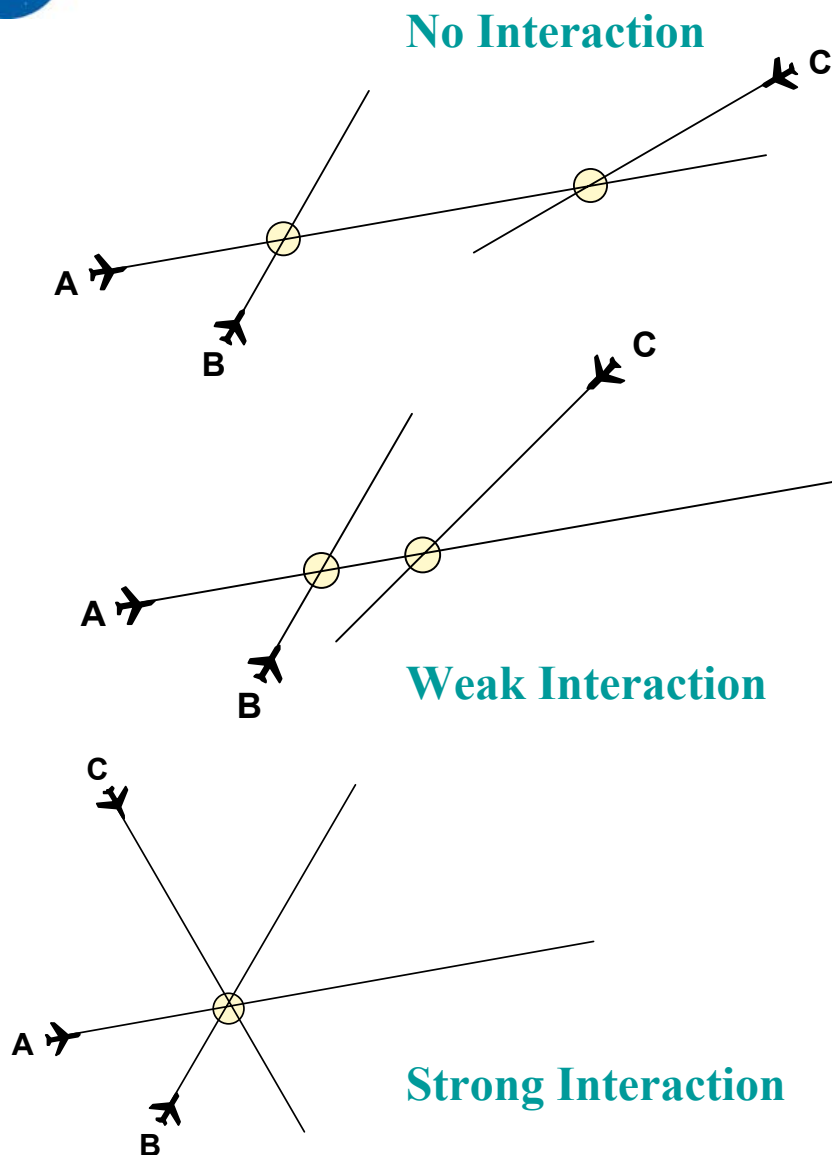None | Weak | Strong

Type of Conflict Interaction

Summary of Study #1

- Investigated conflict properties for free and structured routing in a simulation based on 24 hours of real traffic data (ETMS)
  - Results for conflicts in Class A airspace

- Less than 30% of aircraft ever experienced a conflict
  - Of these, about 40% experienced more than one conflict

- About 75% of conflicts involve only level-flying aircraft

- Most (~85%) conflicts had no significant interaction
  - Useful information for design of conflict resolution tools

- Free routing has ~10% fewer conflicts than structured routing
  - Supports feasibility of Free Flight concept

Performance Evaluation of Airborne Separation Assurance for Free Flight

» **Karl Bilimoria, Kapil Sheth, Hilda Lee, and Shon Grabbe**
Paper No. 2000-4269
AIAA Guidance, Navigation, and Control Conference
Denver, CO
August 2000

- Research Objectives:
  - Study feasibility of airborne separation assurance for free flight
  - Develop techniques to assess performance of CD&R algorithms

- Approach
  - Use two qualitatively different CD&R methods
    » Geometric Optimization approach
    » Modified Potential-Field approach
  - Create a realistic Free Flight traffic scenario
    » Utilize initial conditions obtained from real traffic data
  - Evaluate system performance using metrics
    » Safety
    » Efficiency
    » Stability

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Free Flight Traffic Scenario

- Birth points extracted from Enhanced Traffic Management System (ETMS) data
  - 3 hours of data for Denver Center, from 9 am – 12 noon, on 18 March 1999
  - 955 aircraft in Class A airspace ($\geq$ FL180)

- Free Flight simulation
  - Fly direct route from birth point to destination (great circle navigation)
  - Deviate from nominal trajectory as necessary for conflict resolution
  - Conflict resolutions shared equally
  - Horizontal flight only
    - » Each aircraft flies at its cruise (maximum) altitude found in ETMS tracks


DENVER CENTER AIRSPACE

Denver

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- ## Safety
  - Number of observed conflicts (loss of separation) with CD&R engaged

- ## Efficiency
  - Incremental cost of conflict resolution, measured by:
    » Change in path length (relative to nominal trajectory with no CD&R)
    » Change in flight time (relative to nominal trajectory with no CD&R)

- ## Stability
  - Conflict resolution often creates new conflicts – "domino effect"
    » Number of deviated aircraft that were not nominally in conflict
    » Number of aircraft, nominally in conflict, that were not deviated
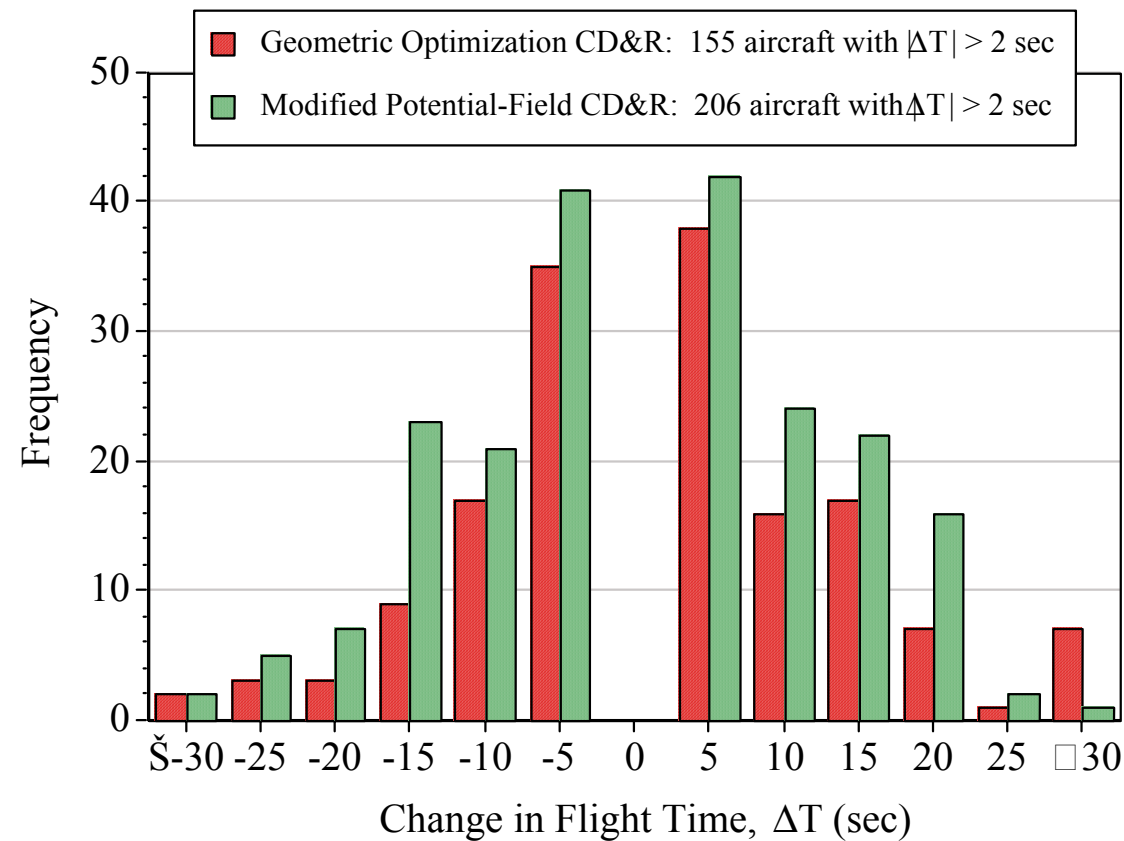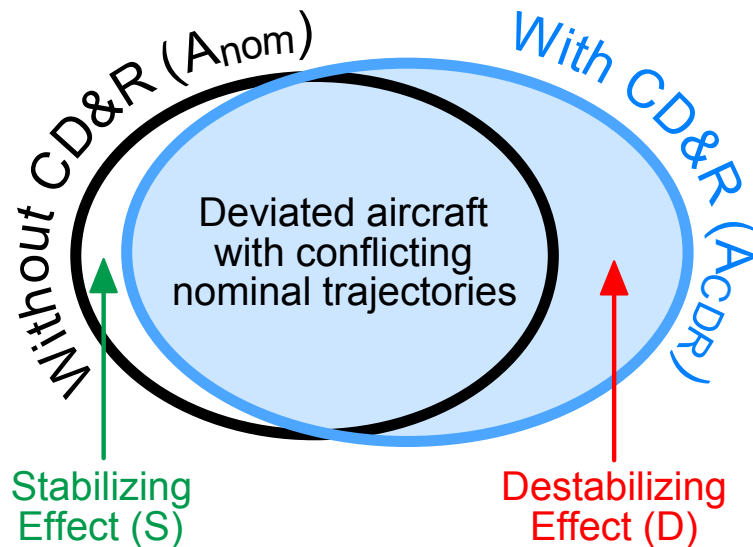
	Geometric Optimization CD&R Method	**Modified Potential-Field CD&R Method**
Count for $\lvert \Delta T \rvert$	155 aircraft	206 aircraft
Sgn. Mean	6 sec	2 sec
Abs. Mean	12 sec	11 sec
Abs. Sum	1810 sec	2226 sec

Stability Results

Without CD&R (A_{nom})

With CD&R (A_{CDR})

Deviated aircraft
with conflicting
nominal trajectories

Stabilizing
Effect (S)

Destabilizing
Effect (D)

	Geometric Optimization CD&R Method	**Modified Potential-Field CD&R Method**
A_{nom}	209	209
A_{CDR}	248	352
D	47	145
S	8	2
DEP	**0.19**	**0.68**

Domino Effect Parameter

$$DEP = \left\lfloor \left(\frac{D}{A_{nom}}\right) - \left(\frac{S}{A_{nom}}\right) \right\rfloor = \left(\frac{D-S}{A_{nom}}\right)$$

Summary of Study #2

- Investigated feasibility of self-separation using a Free Flight traffic scenario constructed from real air traffic data

- All conflicts were resolved

- Deviations of individual trajectories were very small
  - Mean flight-time changes ~10 sec
  - Mean path-length changes ~1 nm

- Impact on system stability is dependent on CR method
  - Percentage of additional aircraft drawn into conflicts ~ 20% to 70%

- These preliminary results support the feasibility of airborne separation assurance for Free Flight

System Performance Characteristics of Centralized and Decentralized Air Traffic Separation Strategies

» **Jimmy Krozel, Mark Peters, Karl Bilimoria, Changkil Lee, and Joseph Mitchell**
»**4th USA/Europe Air Traffic Management R&D Seminar**
»**Santa Fe, NM**
»**December 2001**

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Problem Definition

- Research Questions:
  - Does decentralized CD&R create a domino effect? How strong is it?
  - What does the domino effect do to system-wide trajectory deviations?
  - How does system performance vary with traffic density?

- Approach
  - Simple implementations of two types of separation strategies
    » Centralized: Emphasizes system stability – tries to suppress domino effect
    » Decentralized: Emphasizes efficient resolution of individual conflicts
      ☎ Myopic: Focuses exclusively on aircraft-level efficiency
      ☎ Look-ahead: Gives up some efficiency to gain some stability
  - Run Monte Carlo simulations of free flight, using randomized traffic scenarios
    » Simulate varying traffic densities (up to ~ 5x current peak en route density)
  - Measure domino effect, and determine its impact on trajectory deviations

Monte Carlo Runs

- Run time of 50 minutes for each scenario

- 16 traffic densities

- 18 randomized traffic scenarios at each density (total 288 scenarios)

- Each scenario was run with:
    - Conflict Resolution (CR) off
    - Centralized CR
    - Myopic Decentr. CR
    - Look-ahead Decentr. CR

S_1: Conflict Alerts with Resolution **OFF**

S_2: Conflict Alerts with Resolution **ON**

Common Conflict Alerts (R_2)
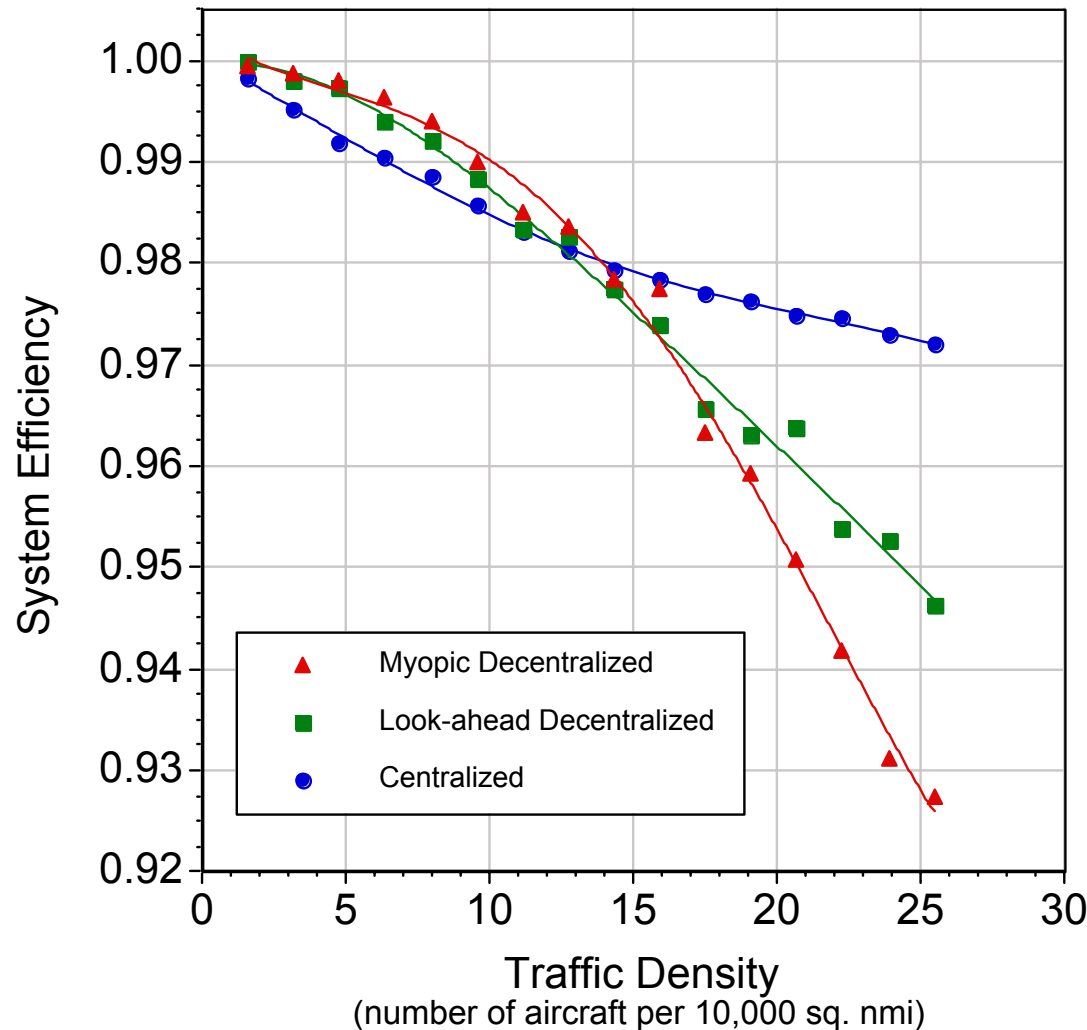
Stabilizing Effect (R_1)

Destabilizing Effect (R_3)
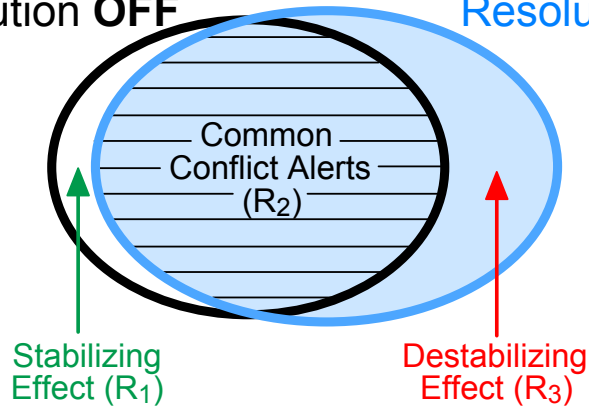
Domino Effect Parameter

$$DEP = \left(\frac{|R_3| - |R_1|}{|S_1|} \right) = \left(\frac{|S_2|}{|S_1|} - 1 \right)$$

Legend:
- ▲ Myopic Decentralized
- ■ Look-ahead Decentralized
- ● Centralized

Y-axis: Domino Effect Parameter (0, 3, 6, 9, 12, 15)

X-axis: Traffic Density (number of aircraft per 10,000 sq. nmi) (0, 5, 10, 15, 20, 25, 30)

$$E_{sys} = \frac{1}{N} \sum_{i=1}^{N} \left(1 - \frac{\Delta l_i}{l_i} \right)$$

Legend:
- ▲ Myopic Decentralized
- ■ Look-ahead Decentralized
- ● Centralized

X-axis: Traffic Density (number of aircraft per 10,000 sq. nmi)
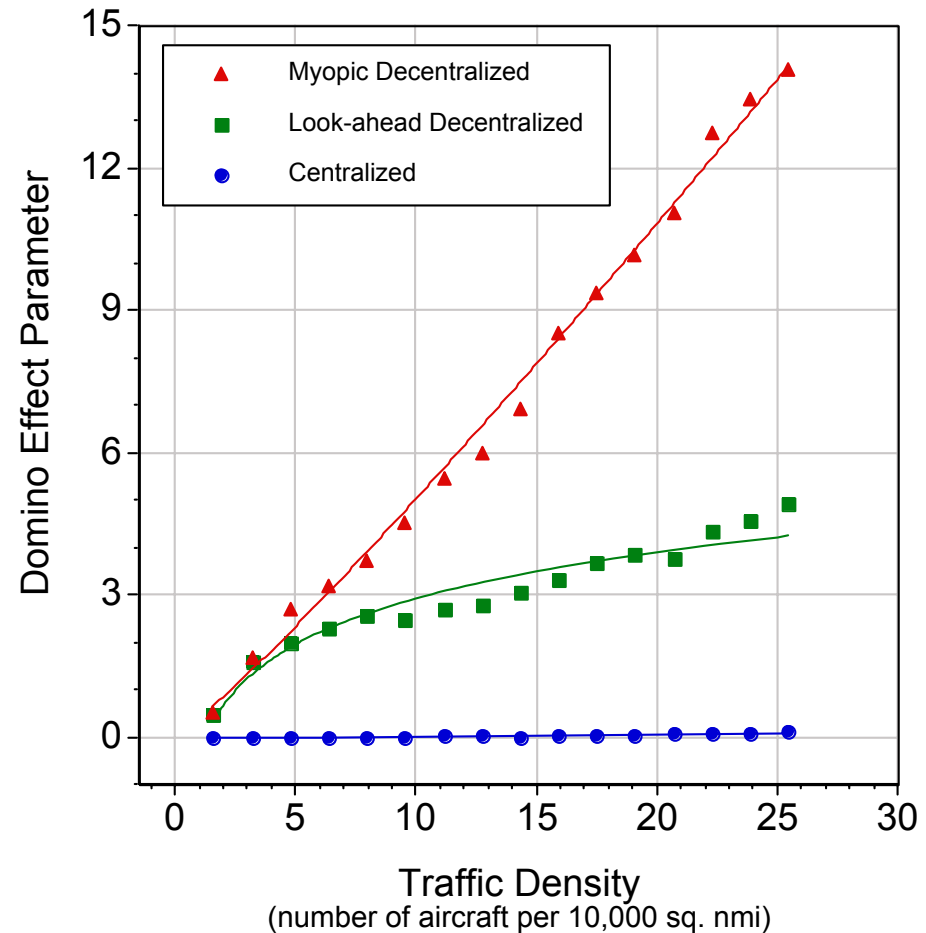
Y-axis: System Efficiency

- Even a 1% change in system efficiency is significant from an operational perspective

- Crossover between Centralized and Decentralized strategies at about 13 a/c per 10^4 sq. nmi

- Crossover between the Myopic and Look-ahead Decentralized strategies at about 16 a/c per 10^4 sq. nmi

Summary of Study #3

- Investigated impact of domino effect on system performance

- System efficiency degrades with increasing traffic density for centralized as well as decentralized separation strategies

- Decentralized separation strategies can create a strong domino effect, especially at very high traffic densities. However,
  - Domino effect does not significantly degrade system efficiency up to a threshold traffic density
  - Threshold density can be increased by adding a look-ahead feature

- Mitigation of domino effect should be an important factor in the design of algorithms for airborne separation systems

Study #4: Stability of Intersecting Streams

- **Objective:** Determine stability characteristics of intersecting streams of aircraft operating under decentralized CD&R rules (self-separation)
  - Developed an analytical proof for stability, and checked it via simulations

- Stability defined as existence of bounds on trajectory deviations

- Determined analytical expression for bounds on trajectory deviations to resolve "streaming" conflicts

- Bound values cross-checked by numerical simulations
  - Excellent agreement

Angular deviation bound ≈ 4 deg
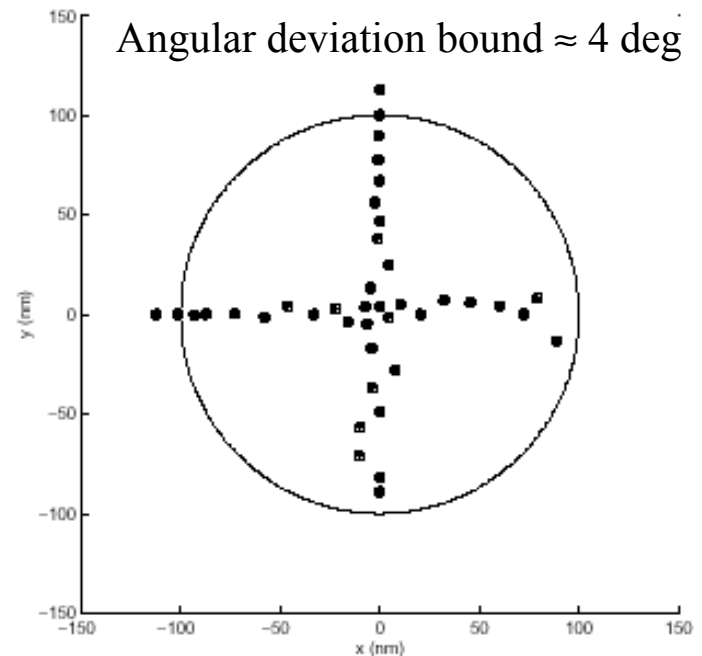
Mao, Z.-H., Feron, E., and Bilimoria, K.D., "Stability and Performance of Intersecting Aircraft Flows under Decentralized Conflict Avoidance Rules," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 2, No. 2, June 2001; and, Dugail, D., Feron, E., and Bilimoria, K.D, "Stability of Intersecting Aircraft Flows using Heading Change Maneuvers for Conflict Avoidance," Paper INV-5005, *American Control Conference*, May 2002

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Aircraft Conflict Resolution with an Arrival Time Constraint

» **Karl Bilimoria and Hilda Lee**
•**Paper No. 2002-4444**
AIAA Guidance, Navigation, and Control Conference
Monterey, CA
August 2002
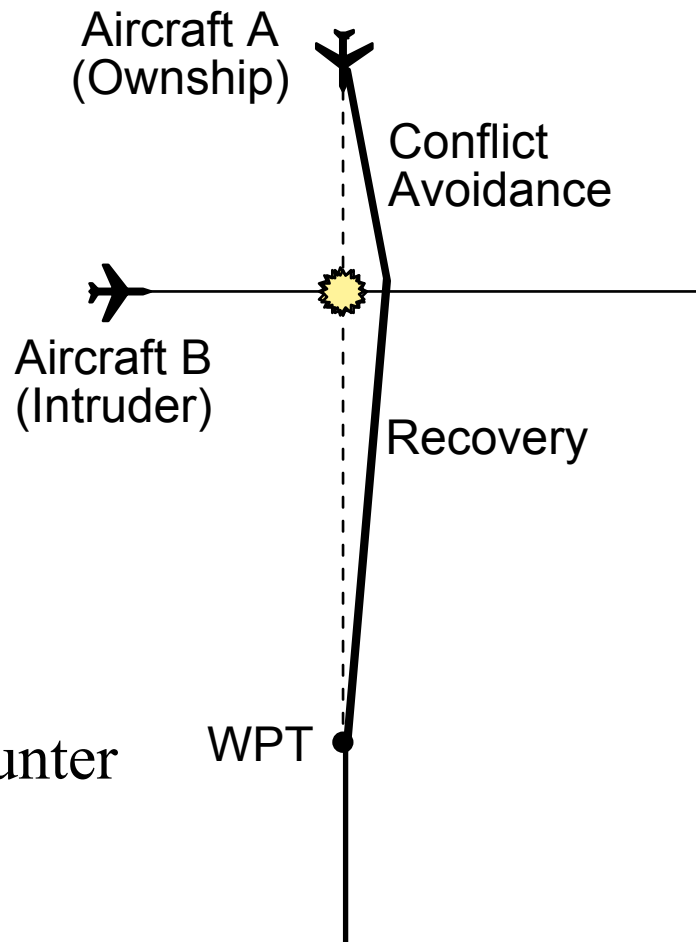
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Problem Definition

- ## Research Objectives:
  - Investigate structure of conflict resolution families with RTA constraints
  - Determine effects of aircraft performance limits on existence of solutions

- ## Approach
  - Extend the Geometric Optimization method to handle RTA constraints
    - » Avoidance solutions: Heading change, Speed change, Optimal (hdg + spd) change
    - » Recovery solution: Change heading to capture WPT; adjust speed to meet RTA
  - Delay Compensated avoidance solution
    - » Avoids conflict using a special combination of heading and speed
    - » Delay caused by path stretching is exactly compensated by speed increase
    - » Recovery speed equals nominal speed
  - Use simple model of aircraft performance (speed and acceleration) limits
  - Conduct parametric study to reveal structure of solutions for conflict resolution with RTA constraint

Parametric Study

- Fundamental parameter for RTA study is $\tau = (t_{FLS} / t_{RTA})$ where $t_{RTA} = (l_{WPT} / V_{NOM})$

- Determined family of CR solutions for 7 values of l_{WPT} : 55, 60, 75, 100, 150, 200, 250 nm

- Computed solution families for 3 encounter angles: 30, 90, 150 degrees

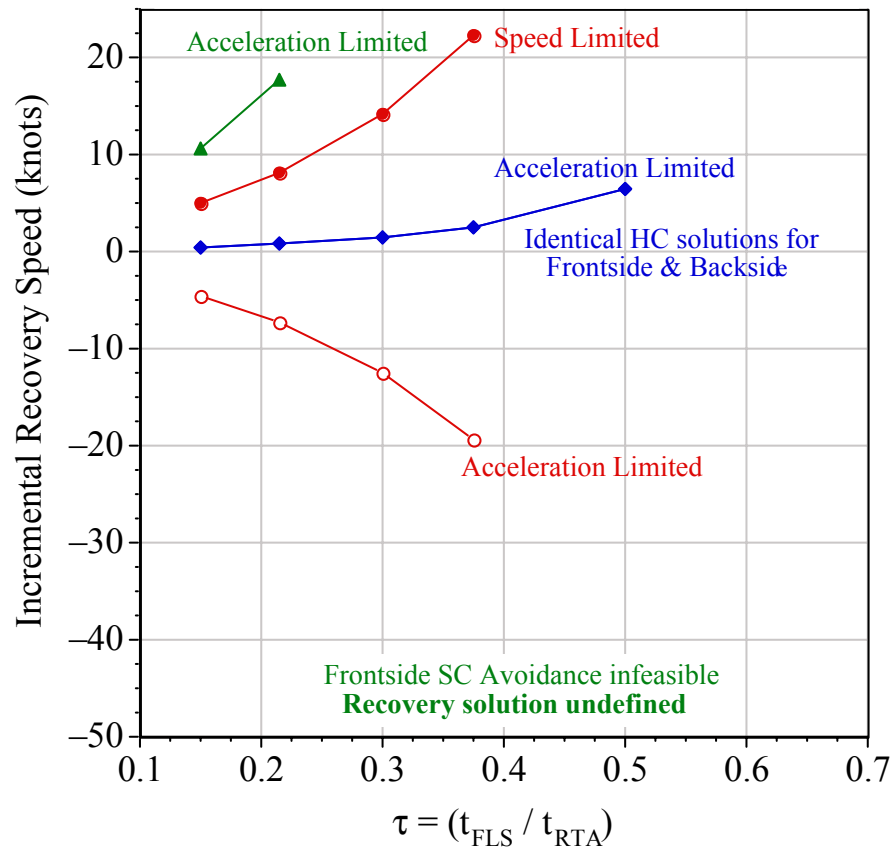- Avoidance: Heading, Speed, Optimal change; Delay Comp.

Aircraft A (Ownship)
Conflict Avoidance
Aircraft B (Intruder)
Recovery
WPT
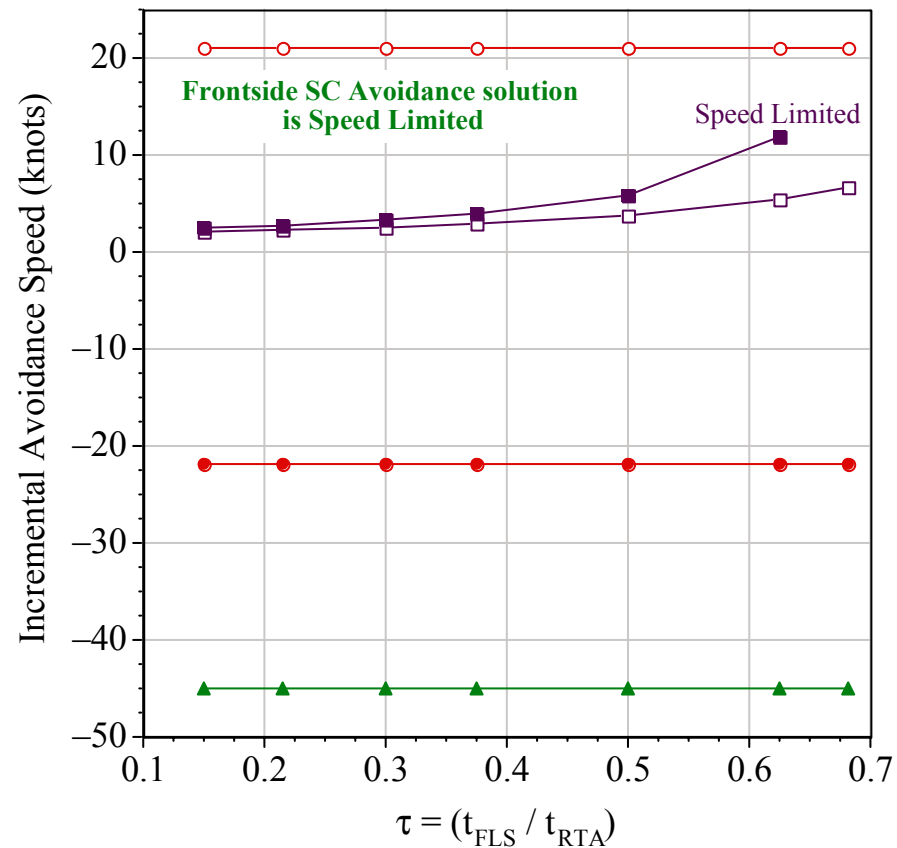
Parametric Study: 30 deg Encounter
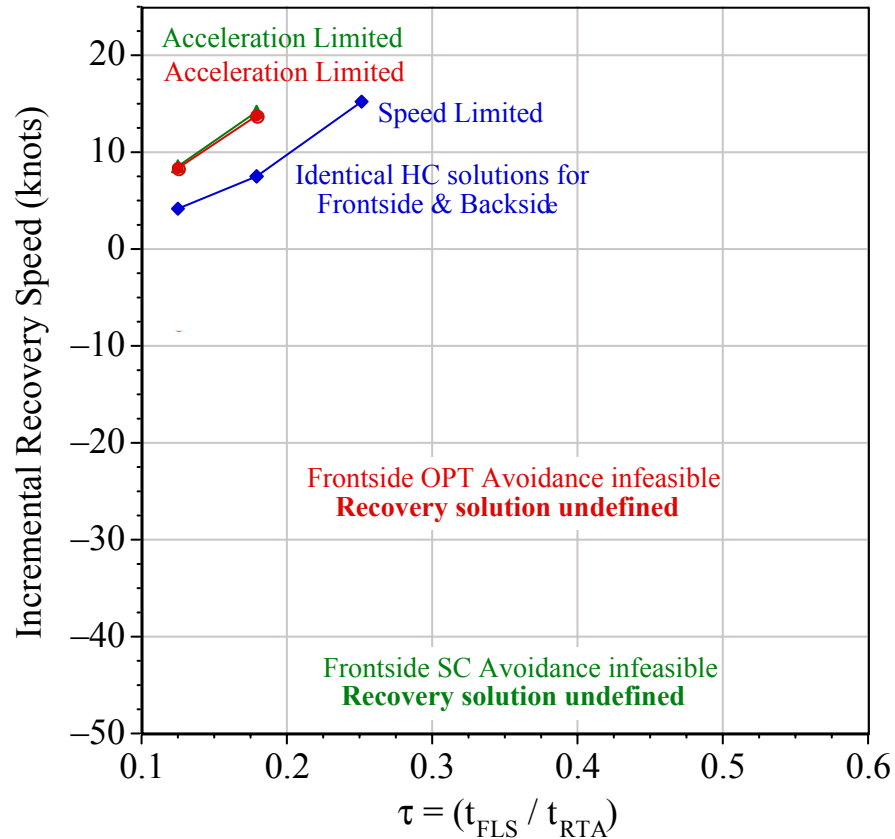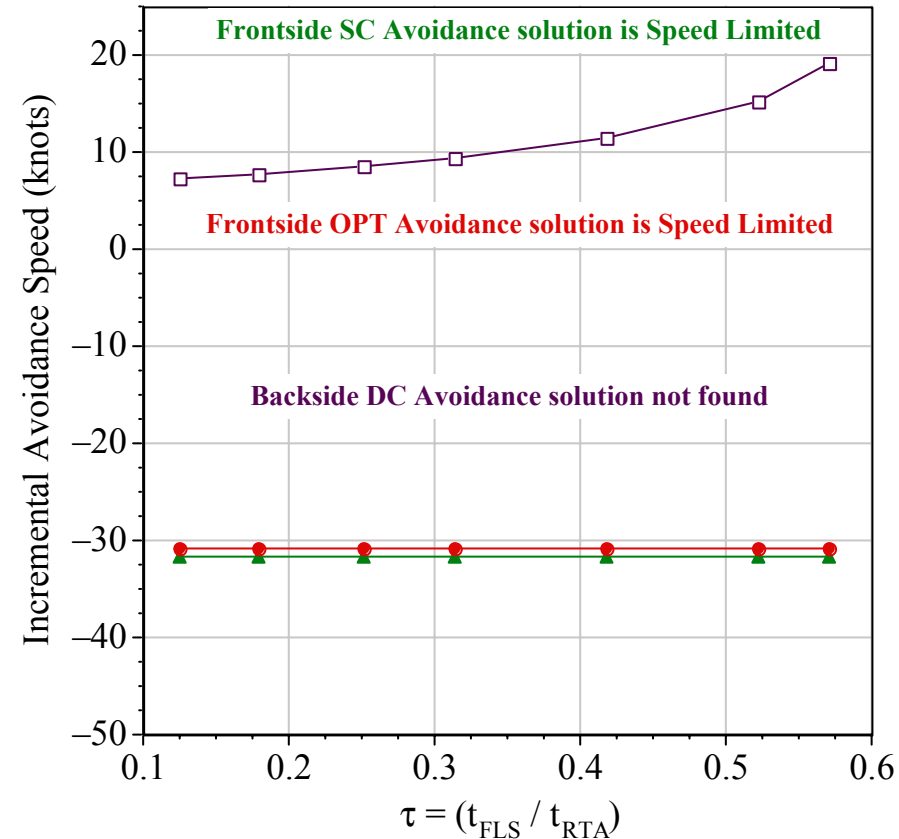
Summary of Study #5

- Generated families of conflict avoidance and recovery solutions, characterized by severity of arrival time (RTA) constraint

- The domain of feasible resolutions is constrained by aircraft performance (speed/acceleration) limits
  - Delay Compensated solution has larger domain of feasibility
  - Other operational solutions could be determined by numerical search

- Required speed often exceeds performance limits if the time to conflict is more than half of the required time to next waypoint

- Prioritization rules for conflict resolution should favor the aircraft that is closer to its RTA

Study #6: Agent-Based Conflict Resolution

- **Objective:** Develop agent-based approach to conflict resolution

- In DAG-TM operations, negotiated resolution of conflicts may be necessary in situations involving constraints: Wx cells, SUA, RTA, etc.

- Pilot and controller agents utilize Principled Negotiation approach

- Starting with a 50-50 split, agents negotiate an equitable solution that satisfies all constraints

- FACET study, using realistic traffic and SUA data for LA Center, shows about 10% of conflicts need negotiation
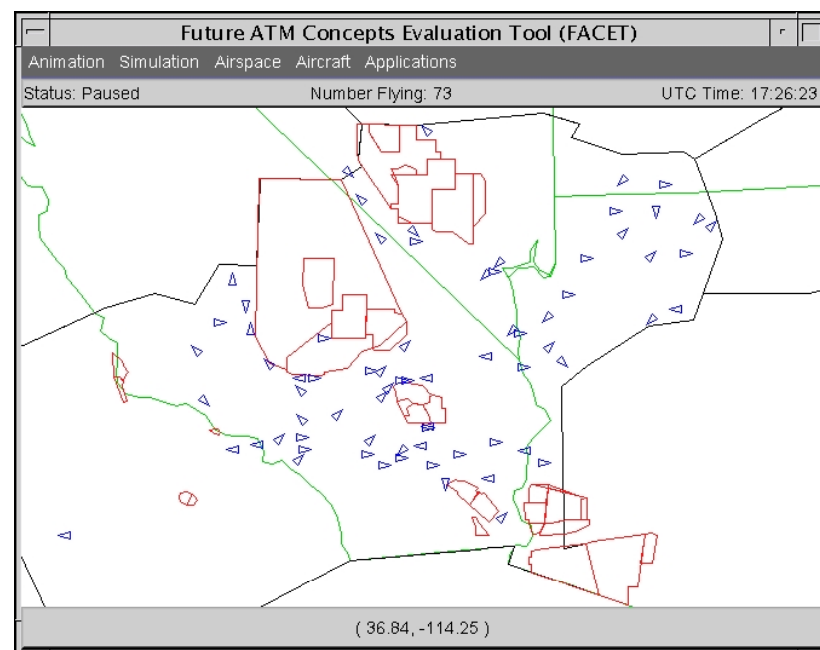
Harper, K.A., Guarino, S.L., Hanson, M.L., Bilimoria, K.D., and Mulfinger, D.G., "An Agent-Based Approach to Aircraft Conflict Resolution with Spatial Constraints," Paper No. 2002-4552, *AIAA Guidance, Navigation and Control Conference,* August 2002.

Constraint Hierarchy

1. ## Aircraft maneuver constraints
   - Hard constraints that are impossible to violate

2. ## Separation constraints
   - Strong constraints that are possible to violate (if extreme conditions warrant doing so), but must generally be respected for safety reasons

3. ## Flow management constraints
   - Constraints that generally do not have a significant impact on safety, if violated on an individual flight basis
   - Violation of these constraints may have a negative effect on the flow of traffic and result in reduced flight efficiency

4. ## User preference constraints
   - Soft constraints that generally do not reduce safety when exceeded
   - There is a cost to the aircraft operator, either directly in terms of dollars or indirectly in terms of passenger dissatisfaction, if these constraints are significantly exceeded

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- Conflicts can be resolved without central coordination
  - Resolved conflicts for traffic scenarios created from real (ETMS) data
  - Resolved multiple-aircraft "converging" conflicts; decentralized solutions showed only ~10% degradation relative to benchmark centralized solutions
  - Derived analytic proof of stable resolutions for "streaming" conflicts

- Trajectory deviations for conflict resolution (distance or time) are very small compared to nominal trajectory length or time
  - Differences in efficiency between various algorithms likely to be quite small
  - Differences in stability could be significant

- Domino effect is not a "show stopper"
  - Trajectory deviations small at current density, even for "myopic" resolutions
  - Significant degradation of efficiency at high (e.g., 3x) densities, but…
  - Degradation can be significantly attenuated by imposing the following rule:
    Resolution of a conflict should not cause any new short-term conflicts

- Conflict Resolution with TFM constraints
  - Required speed often exceeds aircraft performance limits if the time to conflict is more than half of the required time to next waypoint
  - Delay Compensated avoidance maneuver can alleviate this problem
  - Conflict resolution rules should assign priority to aircraft closer to RTA
  - Negotiated resolution can solve highly constrained conflicts

- In en route airspace, at current traffic density:
  - Free routing reduces the number and complexity of conflicts
  - Less than 30% of aircraft ever experienced a conflict
  - Horizontal plane conflicts represent about 75% of total conflicts

- Overall, the results from all studies support the feasibility of Free Maneuvering for user-preferred separation assurance and local-TFM conformance

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Open Research Issues

- Cooperative or non-cooperative conflict resolution?
  - Non-cooperative resolution requires comprehensive and unambiguous flight rules to establish priority
    - » Can these rules be made to work for multiple-aircraft conflicts?
    - » Can these rules be extended to resolution with constraints (SUA, RTA, etc.)?
    - » Is non-cooperative resolution sufficient in highly constrained situations?
  - Cooperative resolution may require more complex procedures and/or algorithms
    - » Can it reduce domino effect at very high traffic densities?
    - » What type of implicit coordination is required?
    - » Is explicit coordination required for highly constrained conflicts?

- Must all "autonomous" aircraft use the same CD&R algorithm?
  - Significant issue for cooperative resolution
 - Less relevant for non-cooperative resolution

Backup Slides

- Developed an algorithm for efficient resolution of aircraft conflicts
  - Seeks to minimize deviations from nominal trajectory
  - Geometric characteristics of aircraft trajectories are utilized to determine closed-form analytical expressions for conflict avoidance commands
    - » Best heading-speed combination
    - » Heading
    - » Speed
    - » Altitude-rate

- Implemented algorithm in ATM simulation environment (FACET)

- Conducted extensive testing with very challenging scenarios
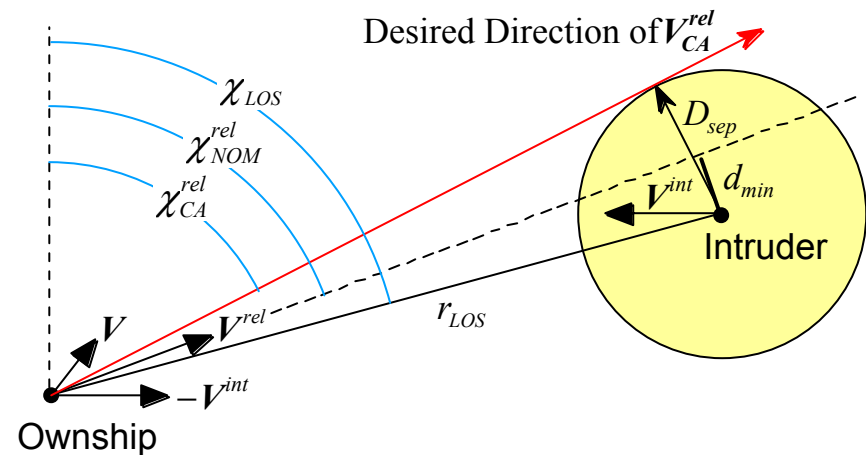
Bilimoria, K.D., "A Geometric Optimization Approach to Aircraft Conflict Resolution," Paper 2000-4265, *AIAA Guidance, Navigation, and Control Conference*, August 2000.
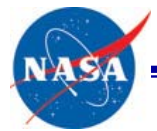
- Formal mathematical verification of the Geometric Optimization CR algorithm conducted at LaRC as part of a safety assessment of DAG-TM
  - e.g., no faults in logic flow, no divisions by zero, always returns solution

- Extended G.O. algorithm for conflict resolution with RTA conformance
  - Determine recovery speed and course to meet RTA at next waypoint
  - Delay Compensated avoidance solution (combination of speed and heading)

- Geometric Optimization CR software may be used for upcoming DAG-TM piloted simulations to study Human Factors aspects of self-separation

- Self-separation studies conducted using Geometric Optimization CR
  - Performance of decentralized CD&R for complex multiple-aircraft problems
    » Works for 8-aircraft problems (28 simultaneous conflicts)
    » Performance degradation (relative to centralized CD&R) is around 10%
  - Feasibility of self-separation in simulated Free Flight with realistic traffic
    » Conducted using FACET